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RADIAL POWER TAILORING FOR A URANIUM DIOXIDE - T-111 CLAD REACTOR WITH CONTAINED FISSION PRODUCT GASES

by Wendell Mayo and Robert M. Westfall

Lewis Research Center
Cleveland, Ohio

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ABSTRACT

A method is presented to evaluate the power capability of a nonvented reactor design which meets required excess reactivity and control requirements without undergoing more than 1 percent diametric creep in the T-111 fuel pin cladding. Optimized 3 fuel zone power tailoring allows a power level of 2.83 megawatts thermal compared to 2.42 for the unzoned reactor. An extension of the method is used to change core size while meeting all other requirements to obtain 3-megawatts-thermal power. The unzoned reactor size is 50.1 centimeters in length and equivalent circular diameter compared to 47.8 for the zoned reactor for 3-megawatts-thermal power.

RADIAL POWER TAILORING FOR A URANIUM DIOXIDE - T-111 CLAD REACTOR WITH CONTAINED FISSION PRODUCT GASES

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SUMMARY

Excess reactivity and control requirements are established for a reference reactor utilizing uranium dioxide fuel pins clad with T-111. Fission product gases are assumed to be contained within the fuel pins for 50 000 hours of operation without producing more than 1 percent diametric creep in the cladding. A method is presented to determine the power capability of both uniformly loaded and power-tailored reactors. The reference core size is 46.9 centimeters in length and equivalent circular diameter. The unzoned reactor is capable of 2.42-megawatts-thermal power. By using 3 fuel zones in the neutronic calculations and optimizing to radial power factors given by stress calculations, the power level can be increased to 2.83 megawatts thermal. It is found that a uniform radial power distribution is not desirable for reactors in which fission product gas generation is the only fuel-clad expanding mechanism.

The method for determining power capability is extended to determine the core size needed to produce 3 megawatts of thermal power. The procedure used combines allowable radial power factor data from stress calculations with core size data from neutronic calculations, both as a function of fuel loading. Thus, while maintaining the required excess reactivity, a core size is determined that will produce the required power for 50 000 hours without exceeding the creep limit of 1 percent.

The unzoned reactor, for 3 megawatts of thermal power, must be 50.1 centimeters in length and equivalent circular diameter compared with 47.8 centimeters for the zoned reactor. The unzoned reactor has 15 percent greater volume than the zoned reactor and requires 7.7 percent more fuel to meet the excess reactivity requirement of 4.9 percent $\Delta k/k$.

INTRODUCTION

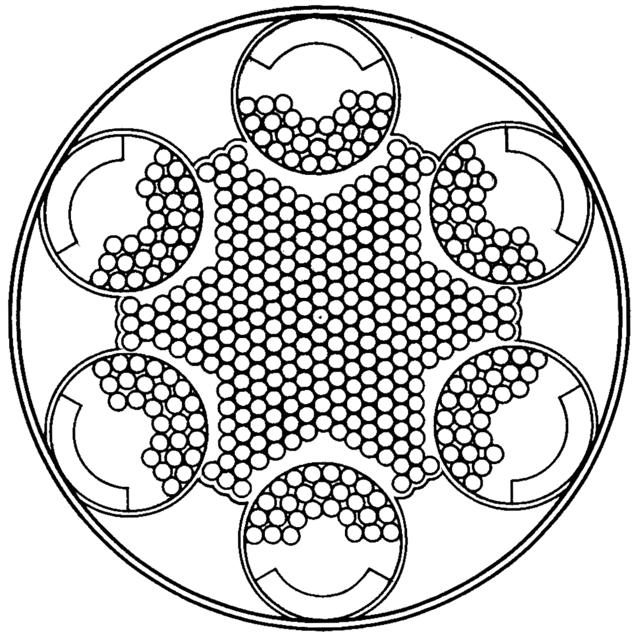
The accumulation of fission product gases in long-lived high-temperature nuclear reactors constitutes a major design problem. Reference 1 discusses some possible fuel element designs that consider either venting or containing fission product gases.

In this report we consider the case of containing fission product gases within the fuel elements of the reactor core. Upon specification of the operating temperature, the fuel pin size, the clad thickness, and the materials of construction, there are three parameters which may be varied to reduce fission gas pressures. These are (1) void fraction in the fuel element, (2) overall power density, and (3) local-to-average power density ratio. Clad thickness is established based on unirradiated stress data assuming no mass transport effects or fuel swelling; the only cladding stress mechanism considered is that from fission product gas release. With the clad thickness fixed, the void content of the fuel element can be increased only at the expense of reduced fuel loading. Thus criticality sets an upper limit on void fraction. Reduction in overall power density can be used to reduce gas pressure. However, if the power level is decreased, the core must be made larger to maintain the same total power capability. Power distribution tailoring can be useful in redistributing gas production more equitably among the fuel pins. This tailoring, by varying void content spatially within the core, allows more fuel pins to operate near the upper limits of allowable gas pressure.

In this report we present an analysis of a pin-type reactor using enriched uranium dioxide (93.2-percent uranium 235) fuel which is clad with the tantalum-base alloy T-111. The reactor is controlled by rotating fueled drums. Excess reactivity and control requirements are established for 50 000 hours of operation at 3-megawatts-thermal power. Stress calculations are used to determine allowable power densities which will limit creep in the cladding to 1 percent. A method is presented to evaluate the reactor in terms of the maximum power allowed which will not result in more than 1 percent creep. Both uniformly-loaded and power-tailored cases are considered. An extension of this method is used to systematically change reactor size while maintaining the required excess reactivity to obtain a desired power level for 50 000 hours of operation without exceeding the creep limit.

REACTOR DESCRIPTION

Figure 1 shows a radial section of the reactor. The lattice shown is a 0.0254-centimeter-thick tantalum alloy (T-111) spacer grid. The fuel pins which fit within the spacer grid tubes have 0.1-centimeter thick flow channels around them. Thus the tube-in-tube design has a constant thickness flow channel around each pin to eliminate circum-



CD-10325-22

Figure 1. - Core and reflector geometry (drums in).

ferential temperature gradients. The grid also reduces the hazard of fuel element bowing. Figure 2 shows a lattice cell in more detail. The cell is depicted as containing portions of four fuel pins instead of a hexagonal cell centered on a fuel pin

The fuel pins are enriched uranium dioxide (93.2-percent uranium 235) clad with 0.127 centimeter of T-111. The outside diameter of the pin is 1.905 centimeters.

The amount of fuel and void inside the pin is variable. For an allowable diametric creep of 1 percent in the cladding, the internal pressure is assumed to be 2600 pounds

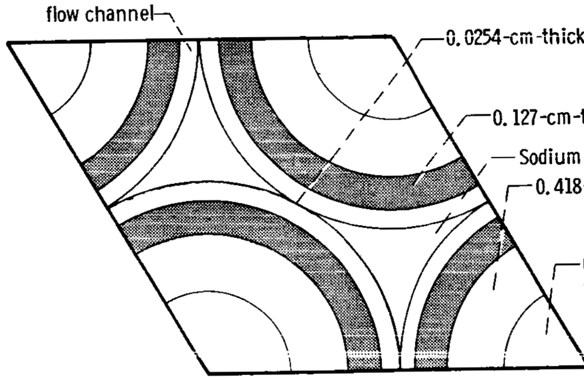


Figure 2. - Lattice cell with fuel and void region dimensions corresponding to fuel volume fraction of 0.372.

per square inch (1.79×10^7 N/m^2) at the end of life. The allowable clad stress is 18 000 pounds per square inch (1.24×10^8 N/m^2).

As in reference 1, it is assumed that 0.3 gaseous atom per fission are released. The stress analysis which was used is also described in reference 1. No other pressure-building mechanism such as fuel swelling is considered. The clad strength is based on unirradiated stress data and possible chemical and mass transport attack of the clad by the sodium coolant are neglected.

The configuration shown in figure 1 contains 427 fuel pins with 162 (38 percent) of the pins located in the six control drums. The 38 percent was selected on the basis of results of fueled drum studies in reference 2. The equivalent circular-fueled core diameter is 46.9 centimeters. The fuel pin length is also 46.9 centimeters. The radial reflector is 10.2-centimeter-thick molybdenum. It contains 15-volume-percent sodium. The pressure vessel is 1-centimeter-thick T-111 and surrounds the radial reflector. The axial reflectors are also 10.2-centimeter-thick molybdenum separated from the core by 2.5-centimeter-thick sodium-distribution plenums at each end of the core.

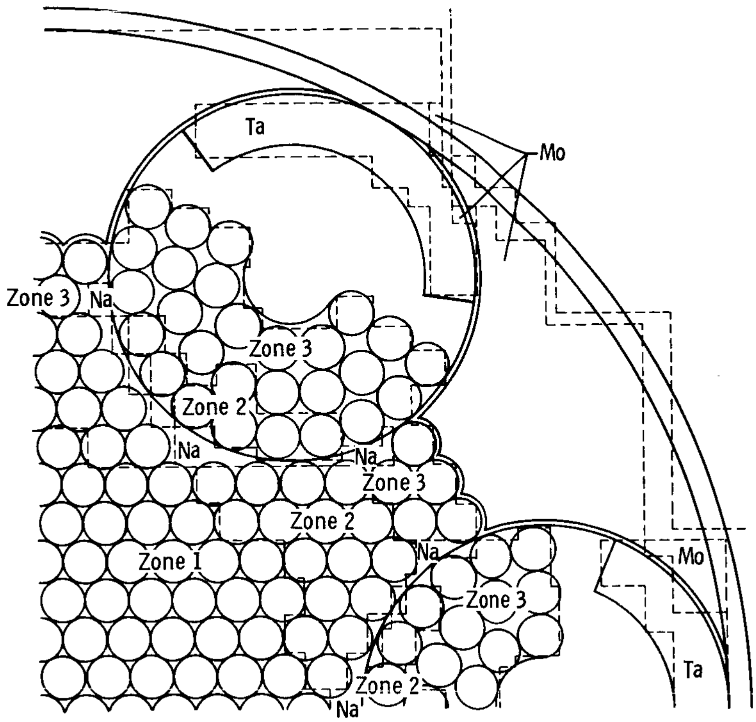
The sodium-coolant volume fraction in a cell is 0.252 and the T-111 volume fraction is 0.218 which includes 0.042 for the spacer grid. The remainder of the cell volume is occupied by fuel and void. The fuel temperature is 1722 K and the bulk temperature is 1222 K.

The control drums are 17.8 centimeters in diameter and contain tantalum segments to enhance control drum worth. Reference 2 indicates that the control drum worth for this size reactor should be about 10 percent $\Delta k/k$. With fuel zoning this worth should increase to about 11 percent $\Delta k/k$.

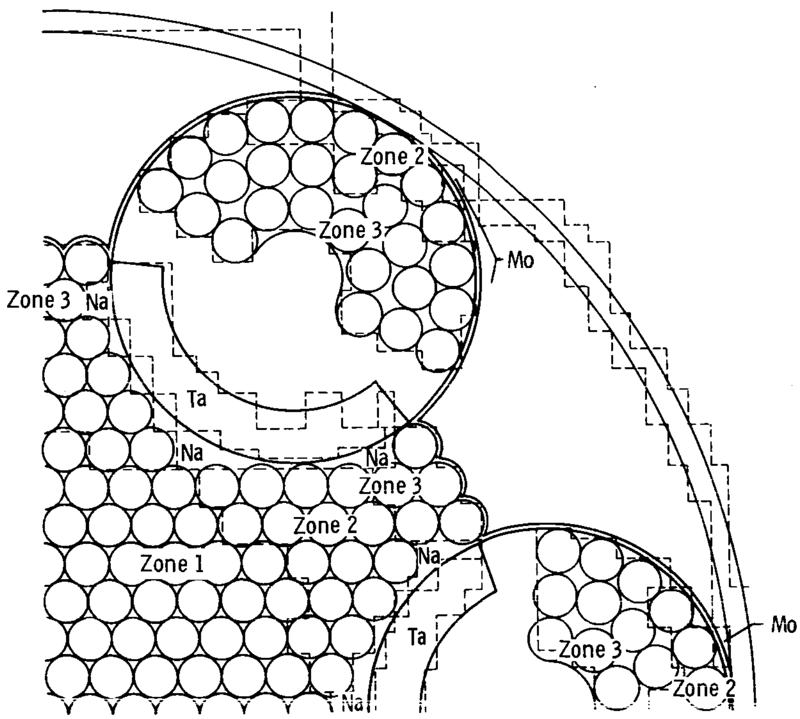
ANALYTICAL METHODS

Geometric Models

Two basic geometric models are used for representing the radial reactor geometry shown in figure 1. Figure 3(a) shows the two-dimensional (x, y) model used for the "drums-in" (drums at most reactive position) calculations. The left and bottom boundaries are plane reflective symmetry boundaries. The dashed x-, y-lines as used in the calculations are shown superimposed over the actual geometry. The interior boundaries are such that the fuel area is based on an integral number of lattice cells as in figure 2, except for the outer region of fuel in the drums. Some additional sodium appears in this region because of the nonuniform lattice. In the zoned reactor the central zone (zone 1) contains 139 fuel cells, the intermediate zone (zone 2) contains 138 fuel cells. Of the 150 fuel cells in the outer zone, 120 are in the drums and these comprise the region with



(a) Fuel drums inserted. CD-10326-22



(b) Fuel drums rotated out. CD-10327-22

Figure 3. - One-fourth core geometry showing two-dimensional calculational geometry (dashed lines) superimposed over actual geometry.

the additional sodium.

Figure 3(b) shows the "drums-out" (drums at least reactive position) geometry. The areas of each material is the same as for the drums-in case.

One-dimensional radial calculations use the model in figure 4. The area of each of the annularized zones is the same as in the two-dimensional drums-in model except that the tantalum-absorber elements in the drums have been homogenized with part of the

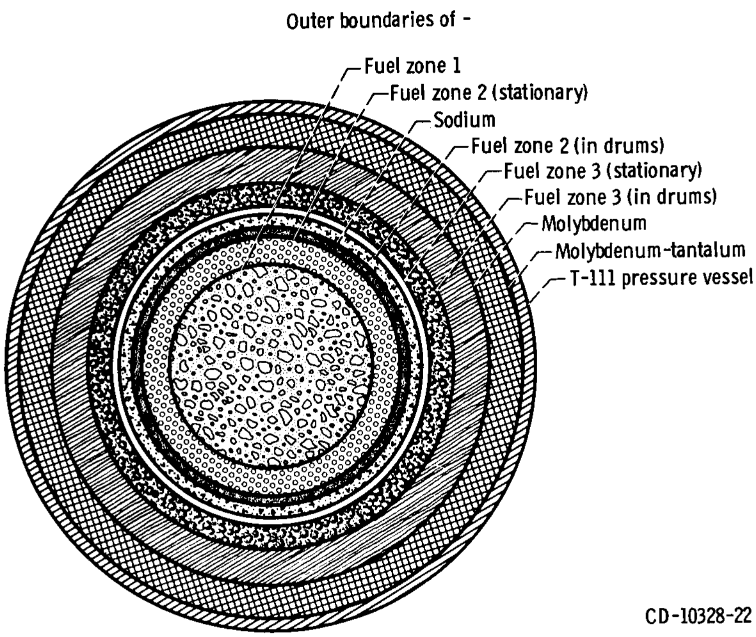


Figure 4. - One-dimensional representation of core geometry with regions of same size as those in two-dimensional geometry.

molybdenum reflector. Also the lithium-6 hydride region outside of the pressure vessel in figure 3 has been omitted; its purpose was to fill in the area outside the pressure vessel in the two-dimensional geometry with a representative shield material which would not affect the neutronics of the reactor. The circular boundaries are treated exactly in the one-dimensional geometry. Thus the shield material is not needed. No drums-out one-dimensional model is required in the present analysis because the power distribution is required only for the hot operating reactor.

Neutronic Calculation Methods

With the absence of significant moderation in this reactor, thermal neutron groups need not be included in the analysis (the median energy of the flux spectrum is ~0.4 MeV). The GAM-II program (ref. 3) is used for obtaining spectrum-averaged broad-group cross sections for 13 energy groups extending down to 0.4 electron volt. The 13-energy group structure is shown in table I. A four-group set is also indicated in table I. The 13-group set was used for all one-dimensional calculations; the four-group set was used for two-dimensional calculations.

TABLE I. - NEUTRON ENERGY GROUP STRUCTURE

Group	Lower energy,[a] eV	Group	Lower energy,[a] eV
1	3.679×10^{6}	8	1.111×10^{5}
2	2.231×10^{6}	9	[b]4.087×10^{4}
3	1.353×10^{6}	10	1.503×10^{4}
4	[b]8.209×10^{5}	11	5.531×10^{3}
5	4.979×10^{5}	12	7.485×10^{2}
6	3.020×10^{5}	13	[b].414
7	[b]1.832×10^{5}		

[a]Upper starting energy 14.9 MeV.
[b]Lower bounds for four-group calculations.

Spatial calculations were done with the TDSN program (ref. 4). The procedure for reducing the order of the multigroup S_4P_0 approximation used in the one-dimensional calculations is similar to the procedure used in reference 2. All calculations of reactivity worth were done using the reactivity difference between two static reactor conditions except for the Doppler temperature defect, which was estimated using the method and equations of reference 5. Thus, for example, the reactivity worth of the temperature-dependent sodium-coolant density is obtained by calculating the reactivity difference between the reactors at two temperatures using the corresponding sodium density at each temperature in the TDSN calculations.

ANALYSIS AND RESULTS

Preliminary Criticality Calculations

Initial neutronic calculations were done to determine parameters for use in subsequent analysis. The first item required is the approximate fuel loading of the reactor with sufficient excess reactivity to serve as a starting point in the radial-power distribution tailoring calculations. Using the average core compositions for the 46.9-centimeter-diameter core described previously, a radial-axial leakage synthesis was performed. The one-dimensional (drums-in) model geometry was assumed in the radial dimension. Axially the reactor was assumed to be symmetric with end reflectors of the same material and thickness as the radial reflector but separated from the core by a 2.5-centimeter-thick plenum region composed mostly of sodium. Fully converged synthesis calculations for a 46.9-centimeter-diameter core gave a multiplication factor of 1.063 with an average fuel loading of 0.372 core volume fraction. The axial maximum-to-average power ratio was 1.25 and was assumed constant in all subsequent analyses.

The synthesis calculation for the 46.9-centimeter-diameter reactor was also used to obtain an effective buckling height for use in all the other radial calculations described in following sections. It was found that augmenting the actual core height, H, by 13.4 centimeters yielded the same multiplication factor (from radial calculations) as the synthesis method. Thus the transverse leakage is based upon a group-dependent axial buckling given by

$$\frac{\pi^2}{\left(H + 13.4 + 2\delta_g\right)^2}$$

where δ_g is the extrapolation distance for group g computed as 0.71 times the transport mean free path.

Reactivity and Reactivity Control Requirements

The one-dimensional unzoned reactor model was used to establish the reactivity and reactivity control requirements for the reactor. The excess reactivity that must be controlled consists of the cold-to-hot temperature defect and the reactivity for fuel depletion. Enough additional control is required for some cold shutdown margin and to allow for the possibility of one drum being struck at its most reactive position.

Cold-to-hot temperature defect. - This is made up of the temperature expansion of the core materials and the Doppler temperature defect. The core and sodium coolant expand at different rates but together amount to -1.4 percent $\Delta k/k$ from 371 K (the melting point of sodium) to 1222 K (operating temperature). The sodium density change alone between these temperatures is worth -0.7 percent $\Delta k/k$. The sodium density in both core and reflector was decreased. For the core expansion calculations, which also gave -0.7 percent $\Delta k/k$, the linear expansion coefficients used were:

$$5.5\times10^{-6}\ \mathrm{cm/(cm)(K)} \qquad \text{for molybdenum}$$

$$6.3\times10^{-6}\ \mathrm{cm/(cm)(K)} \qquad \text{for T-111}$$

The atom densities in the core and in the reflector were reduced in proportion to the volumetric expansion thus preserving the total core inventory of atoms.

The Doppler temperature defect was estimated to be not more than -2 percent $\Delta k/k$ between 371 and 1222 K. The technique and data for this estimation are from reference 5. Basically the method is a correlation of a limited amount of experimental data from several measurements (some in different reactors) by least-squares fitting of

$$\left.\frac{1}{\rho^i}\frac{\partial \rho^i}{\partial T}\right)_D = AT^{\gamma}$$

where $\left.\frac{\partial \rho^i}{\partial T}\right)_D$ is the measured Doppler coefficient for material i, ρ^i is the reactivity worth of the sample of material at ambient temperature, A and γ are fitting parameters, and T is the temperature in K. The normalization by ρ^i is to remove the spectral dependence of the different fast-spectrum reactors (median fission energies > 50 keV) used for the experiments. Arguments are presented in reference 5 to demonstrate that this is a reasonable normalization.

In the present reactor the tantalum is the most important contributor to the Doppler effect. Tungsten is next in importance; the tungsten alone is sufficient to counteract the small positive contribution from uranium 235. The use of infinitely dilute reactivity worths in the integrated equations of reference 5 leads to the -2 percent $\Delta k/k$ Doppler temperature defect mentioned previously. Resonance self-shielding could reduce the magnitude by a large amount, perhaps more than 50 percent, but for determining reactivity control requirements the conservative value of -2 percent $\Delta k/k$ is assumed.

It might be mentioned at this point that positive reactivity coefficients due to inadvertent core compression have been calculated for several fast-spectrum reactors (refs. 6 and 7). A value of 3×10^{-6} $(\Delta k/k)/\mathrm{cm}^3$ was calculated for the present reactor for radial compression; axial compression in pin-type geometry is unlikely to occur. The method used is described in reference 7. The Doppler coefficient is the only prompt control mechanism available to counteract this positive reactivity coefficient. The core must be supported in such a way as to minimize compressive fuel movement and the Doppler coefficient must be large enough to provide prompt stability.

Fuel depletion reactivity worth. - The reactivity loss due to fuel depletion is estimated using a calculated fuel coefficient of reactivity and the total energy required over the operating lifetime. The fuel coefficient was calculated by perturbing the uranium 235 loading and computing the reactivity due to the perturbation; $\Delta k/k = 0.6\ \Delta M/M$ was obtained where M is the mass of uranium 235 in the core. With 2.46 atom percent burnup required to yield the total energy, the reactivity loss due to depletion is $2.46 \times 0.6 = 1.5$ percent $\Delta k/k$ which is part of the control requirement. This procedure is adequate since the burnup is small.

Reactivity margins for shutdown. - A large fraction of the control requirements is made up of shutdown margins in which -2 percent $\Delta k/k$ for cold shutdown and -3 percent $\Delta k/k$ for the case of one drum stuck in its most reactive position are allowed. For prestartup, an additional -2.3 percent $\Delta k/k$ was calculated due to the absence of sodium in the core in the cold condition. This is not part of the control requirements but is additional margin available prior to startup.

Summary of control requirements. - The reactivity control requirements are, in percent $\Delta k/k$:

Cold-to-hot temperature defect		3.4
Doppler	2.0	
Core expansion	0.7	
Sodium density	0.7	
Fuel depletion		1.5
Shutdown margin		2.0
One drum stuck margin		3.0
Minimum total requirement		9.9

The required multiplication factor (for 4.9 percent $\Delta k/k$ excess reactivity) for this reactor is about 1.052 as a minimum value which includes the cold-to-hot temperature defect and the reactivity for fuel depletion.

The preliminary one-dimensional calculations indicate an adequate multiplication factor for the unzoned reactor with a fuel volume fraction 0.372 and the control requirements are less than the 11 percent $\Delta k/k$ drum control worth expected from the studies in reference 2.

Maximum Allowable Radial Power Factors

The data from the stress calculations that is used in this present study can be summarized in a set of curves relating radial power factor, P_R (defined as the ratio of average power in a fuel pin cell to the average power in the core) to the volume fraction of fuel in the cell. Figure 5 shows one of these curves. This curve is for the reference

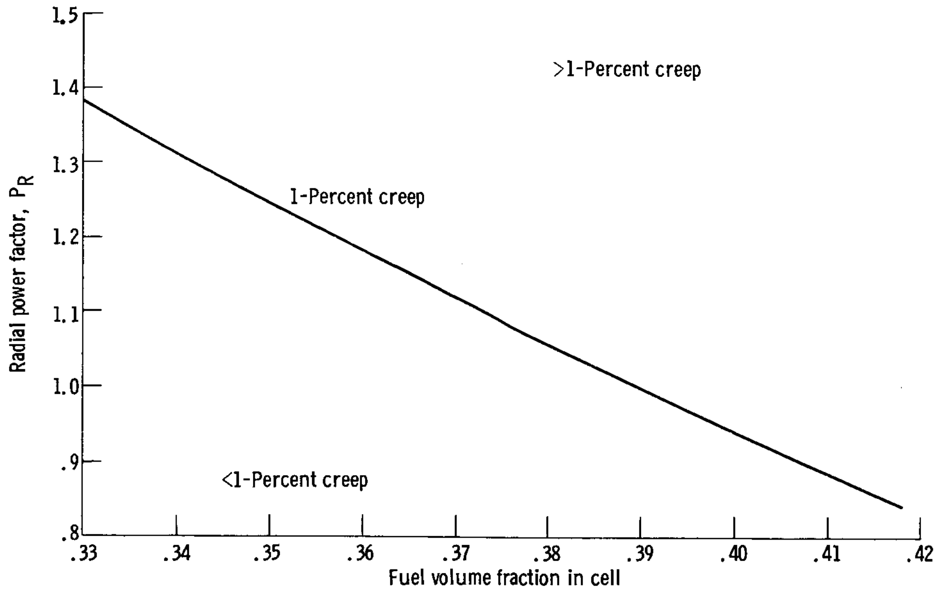


Figure 5. - Maximum allowable radial power factor for reference core conditions.

core conditions in which the power is 3 megawatts thermal for 50 000 hours, and the other parameters such as clad thickness and temperature are as described previously. The curve shows the maximum allowable radial power factor for a range of fuel volume fractions in the cell for 1-percent creep. If P_R for the reference core is above the curve for any fuel pin, the creep limit will be exceeded and the fuel volume fraction must be reduced in order to tolerate the P_R or the power density must be reduced. Reducing the power density by lowering the power rating of the core shifts this curve up the ordinate to higher allowable P_R values. Thus, by varying the power rating for the core, a series of curves can be generated, each curve representing maximum allowable radial power factors for that power level as a function of cell fuel loading.

Power Rating for Reference Reactor

The two-dimensional geometry of figure 3(a) with an average fuel volume fraction of 0.372 was used to calculate P_R for the zoned and unzoned reference reactor. Since the P_R that is pertinent to the stress calculation is the time average over core life, the values computed using the drums-in geometry must be modified. From the 1.5 percent $\Delta k/k$ burnup requirement, the anticipated control of 11 percent $\Delta k/k$ and the power ratio versus fuel drum rotation data of reference 2, it was estimated that the average P_R value is 5 percent greater than the value from the end-of-life (or drums-in) geometry at the center of the unzoned core. For the zoned core, a 5-percent increase was assumed

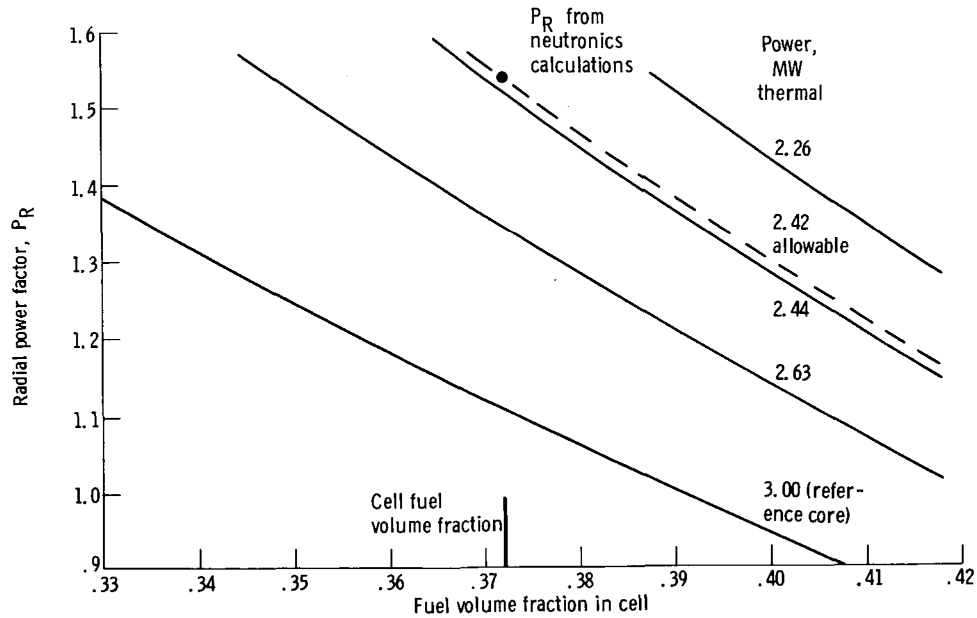


Figure 6. - Determination of allowable power from unzoned reference reactor to limit creep to 1 percent.

for the central zone. No correction was applied to the intermediate zone and -5 percent was used for the outer zone. All P_R values used in this report have been modified by these correction factors.

Figure 6 shows how the allowable power from the unzoned reference reactor is determined. The P_R of 1.54 from the neutronics calculation is shown plotted at 0.372 fuel volume fraction. The point is above the allowable P_R curve for the 3-megawatt-thermal reference core indicating that the 1-percent creep limit is exceeded. Interpolation between the other power level lines determined from the stress calculations shows that the P_R lies on a power line of 2.42 megawatts thermal. Thus the reference unzoned core has to be derated to 2.42 megawatts thermal in order to meet the creep limit of 1 percent.

The multiplication factor for this core size and loading is 1.054, which is only 0.009 Δk less than the one-dimensional result. The radial power factor for the unzoned reactor is also predicted by the one-dimensional model to within 1 percent of the two-dimensional result.

Figure 7 shows how the power rating of the zoned reference reactor is determined. Three fuel zones are used. The central zone (1) contains 139 fuel pins, the intermediate zone (2) contains 138 fuel pins, and the outer zone (3) contains 150 fuel pins. The fuel volume fractions are 0.348, 0.378, and 0.412, respectively. The average fuel volume fraction in a cell is 0.380. The P_R for each zone is shown on figure 8 at the corresponding fuel volume fraction for the zone. The dashed line is drawn through the P_R value farthest from the 3-megawatt-thermal reference core line with approximately the

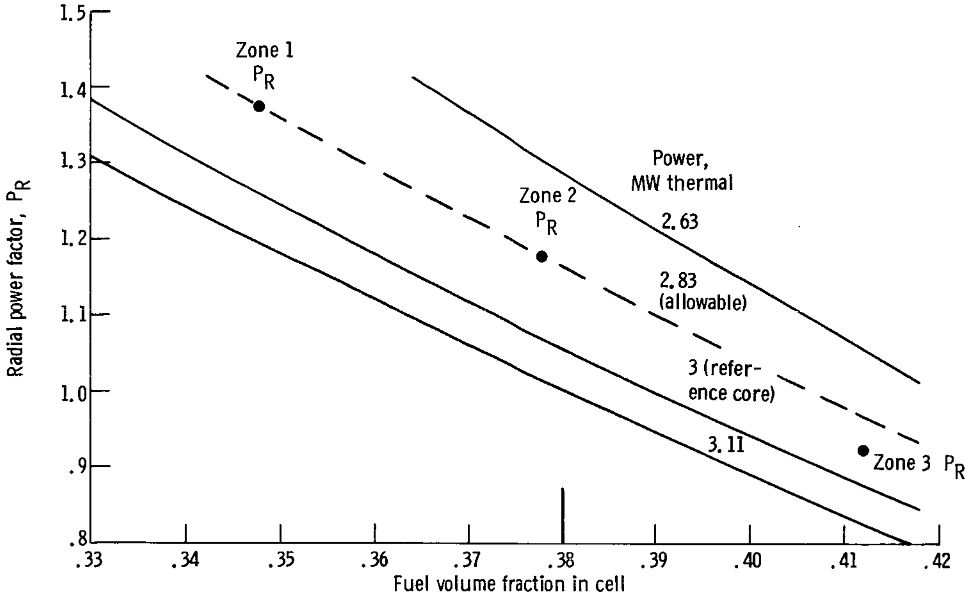


Figure 7. - Determination of allowable power from reference reactor (three zone) to limit creep to 1 percent. (Radial power factor points P_R are from neutronic calculations.)

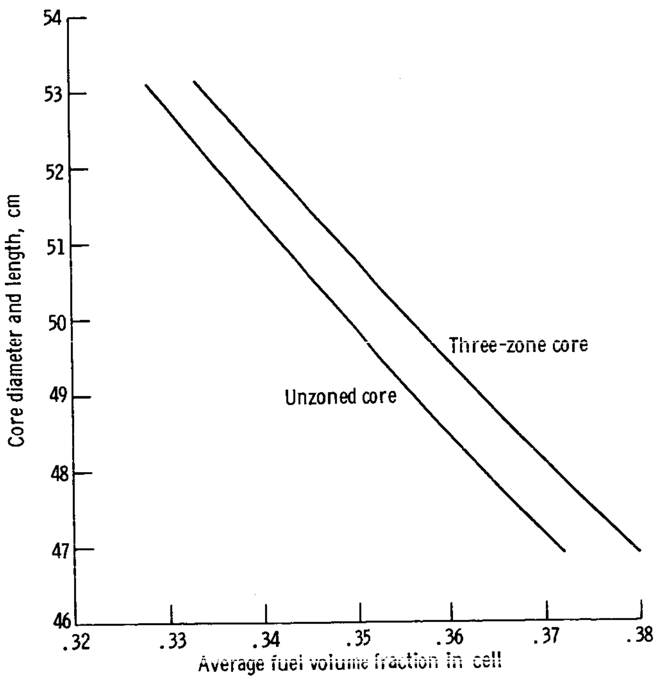


Figure 8. - Core size as function of average fuel volume fraction in cells for constant multiplication factor.

same shape as the 3-megawatt-thermal line. Interpolation of the power lines gives 2.83 megawatts thermal for the allowable power. This level of 2.83 megawatts thermal compared with the 2.42-megawatt-thermal power for the unzoned reactor illustrates the power benefit by fuel zoning. The small increase in average loading from 0.372 to 0.380 in the average fuel cell represents the cost of zoning. In terms of reactivity, this cost is 1.22 percent $\Delta k/k$. The multiplication factor for this zoned core is 1.053 from the two-dimensional calculation. The corresponding multiplication factor using the one-dimensional model is 1.061, only 0.008 Δk too high. The one-dimensional calculations gave the same P_R for zone 1 but was 4 percent low in zone 2 and 2 percent low in zone 3.

Again referring to figure 7, note that the zone 3 P_R lies below the 2.83-megawatt-thermal line. This zone will experience less than 1-percent creep in the cladding. Further refinement in the zoning was not done because the very small changes in fuel volume fractions required are probably not attainable in fuel pin production without extremely tight production control.

Minimum Core Size for 3-Megawatt-Thermal Power

It was shown in the previous section that the reference core with 427 fuel pins was not capable of producing 3 megawatts thermal for 50 000 hours without exceeding the 1-percent creep limit. Both the unzoned and zoned reactor required a lower power density and this reduced power density was obtained by decreasing the overall power level. One could, however, reduce the power density by increasing core size to produce 3 megawatts thermal. If the core is made larger by adding fuel pins of the same size as used in the reference core the creep analysis and P_R versus fuel volume fraction curves would be valid even if the pins were made somewhat longer. If, however, the core size was increased by enlarging pin diameter, the stress analysis would have to be redone for the new pin geometry. In the following analysis it is assumed that core size increases are made by increasing the number of fuel pins and that the length increase is in proportion to the increase in equivalent circular diameter of the core based on a uniform cell lattice.

Figure 8 shows how the core size changes with average loading in a fuel cell for a constant multiplication factor for both unzoned and zoned cores. The multiplication factor for each curve is the same as from the corresponding two-dimensional calculation with the reference core size of 46.9-centimeter length and equivalent circular diameter. The fuel volume fraction in each of the 3 zones of the zoned core was changed in proportion to the change in average fuel volume fraction.

The curves of figure 8 along with the data from the stress calculations such as in figure 5 provide a way of systematically changing the reference core size to produce 3 megawatts thermal without exceeding the creep limit and at the same time maintaining the required multiplication factor. Figure 9 shows this procedure for the unzoned reactor. The

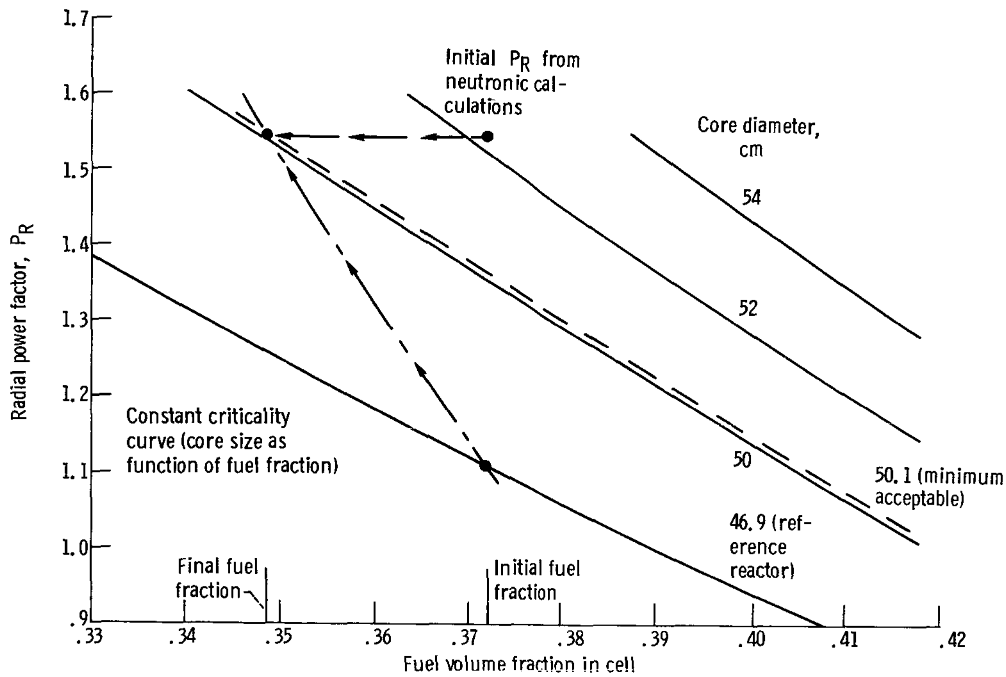


Figure 9. - Determination of minimum acceptable core (unzoned) size for 3 megawatts thermal with 1-percent creep.

criticality curve from figure 8 has been superimposed (broken line) on the P_R versus fuel volume fraction curve and the parameter has been changed from power level for a 427 pin core to core size for 3-megawatt-thermal power. The quantity in common is the power density used in generating these curves. Thus the 3-megawatt-thermal power line in figure 6 is the same line as the 46.9-centimeter core size time in figure 9 since the power density is the same. Curves for 50, 52, and 54 centimeter core size with power densities corresponding to 2.63, 2.44, and 2.26 megawatts thermal for 427 fuel pins are also shown.

Core size is increased by moving along the criticality curve in the direction of lower fuel loadings and higher allowable radial power factors until the criticality curve meets the calculated P_R. This point lies on a core size curve of 50.1 centimeters. The P_R values do not change significantly over the range of core sizes considered here.

The procedure is similar for the 3 zone reactor. The P_R value that is farthest from the 46.9-centimeter reference core size line determines the zone that is limiting and the core size is adjusted accordingly. On figure 10 zone 1 is limiting. The fuel volume fraction in zone 1 is changed in proportion to the change in average cell fuel volume fraction until the point on the criticality curve and the P_R point lie on a line parallel to the reference core size line. The minimum acceptable core size is determined by interpolation to be 47.8 centimeters. The fuel fraction for zones 2 and 3 are then reduced by the same proportion as the change in average cell fuel fraction. Thus the relative ratios

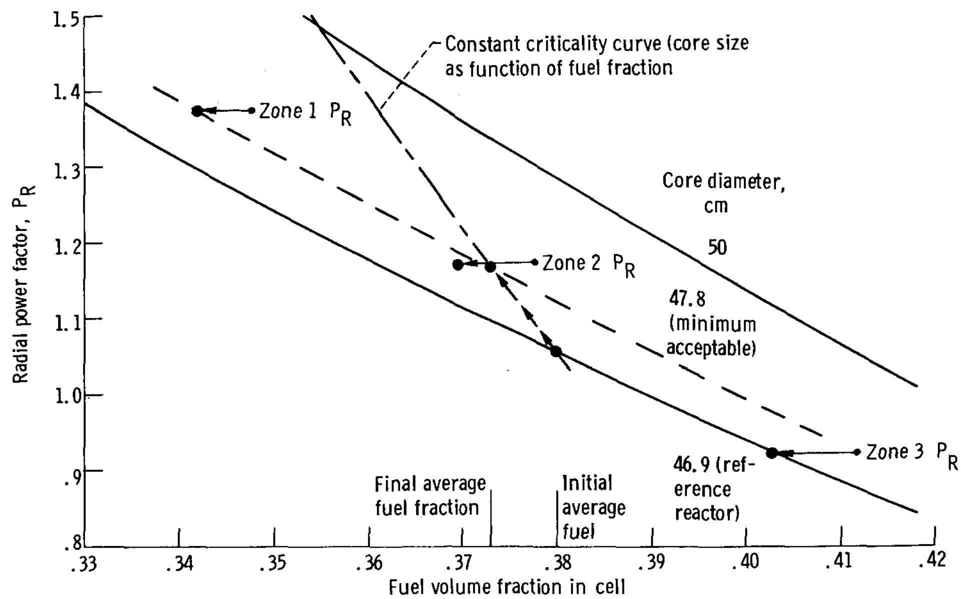


Figure 10. - Determination of minimum core (three-zone reactor) size for 3 megawatts thermal with 1-percent creep. (Radial power factor points P_R are from neutronic calculations.)

of fuel fractions in each zone before and after changing core size is unchanged.

This same procedure is applicable for more than three zones but additional zoning was not done for this reactor. It should also be noted that with the stress calculations summarized as P_R versus cell fuel volume fraction curves the procedure is quite general. With additional refinements in the stress calculations to include fuel swelling effects, or the use of experimental data to determine the curves, the allowable radial power factor curves can show what degree of zoning is optimum and provide a way of evaluating a reactor design.

The 50.1-centimeter size unzoned reactor is 15 percent larger in volume and requires 7.7 percent more fuel than the 47.8-centimeter size 3 zone reactor. Thus, for a 3-megawatt power rating for 50 000 hours, zoning is of value.

Reactivity Worth of Control Drums

The calculation for control drum worth was done using the 3 zone fuel volume fractions of 0.348, 0.378, and 0.412 for the reference core size of 46.9 centimeters. The drums-out geometry of figure 3(b) gave a multiplication factor of 0.930. The reactivity difference between the drums-in geometry with a k of 1.053 and the drums-out geometry is 12.6 percent $\Delta k/k$. The required worth was only 9.9 percent $\Delta k/k$. It is felt that this control worth would also be adequate for the unzoned reactors of 46.9- and 50.1-centimeter size and for the zoned reactor of 47.8-centimeter size.

SUMMARY OF RESULTS

Excess reactivity and control requirements are established for a reference reactor utilizing uranium dioxide fuel pins clad with the tantalum alloy T-111. Fission product gases are to be contained within the fuel pins for 50 000 hours of operation without producing more than 1-percent creep in the cladding. A method is presented to determine the power capability of both the uniformly-loaded and the power-tailored reactor which is 46.9 centimeters in length and equivalent circular diameter. It is found that the unzoned reactor is capable of 2.42-megawatts-thermal power. By using 3 fuel zones and optimizing to radial power factor distributions given by stress calculations, the power level for this reactor is increased to 2.83 megawatts thermal. A uniform power distribution is not desirable for reactors in which fission gas pressure is the only pressure-building mechanism.

The method for determining power capability is extended to determine core size needed to produce 3 megawatts of thermal power. The unzoned reactor must be 50.1 centimeters in length and in equivalent circular diameter while the optimum 3 zone configuration can be 47.8 centimeters. The unzoned reactor has 15 percent more volume and requires 7.7 percent more fuel. The fuel volume fraction in a cell of the unzoned reactor is 0.349 and the average cell in the zoned reactor has 0.373 volume fraction of fuel. The procedure for changing core size utilizes constant multiplication factor curves to maintain the desired criticality characteristics.

The cold-to-hot temperature defect is 3.4 percent $\Delta k/k$ of which 2 percent is estimated for the Doppler effect. The remainder of 1.4 percent $\Delta k/k$ is due equally to core expansion and to sodium-coolant expansion. Fuel depletion requires 1.5 percent $\Delta k/k$, thus the total excess reactivity requirement is 4.9 percent $\Delta k/k$ corresponding to a cold, beginning-of-life multiplication factor of 1.052. The reactivity control requirement of 9.9 percent includes 2 percent for normal shutdown and 3 percent for the case of one drum stuck in its most reactive position. Both the unzoned and zoned reactors meet these requirements for excess reactivity and control drum worth.

A one-dimensional model was compared to the two-dimensional drums-in model used in the calculation of radial power factors and multiplication factors. The multiplication factors from the one-dimensional calculation were less than 1 percent too high. The power factors calculated at the center of the zoned and unzoned reactor were within 1 percent of the two-dimensional result but in the middle zone and in the outer zone, a -4 percent and -2 percent discrepancy was observed, respectively, when using the one-dimensional model.

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